



# Fermi National Accelerator Laboratory

CONF-880288--4  
FERMILAB-Conf-88/45-A  
April 1988

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

## SUPERNOVA 1987A; ONE YEAR LATER A Summary of the La Thuile Symposium\*

David N. Schramm  
The University of Chicago  
Chicago, IL 60637,

FNAL/C--88/45-A

DE88 011147

NASA/Fermilab Astrophysics Center  
Fermi National Accelerator Laboratory  
Box 500, Batavia, IL 60510-0500

and

The Max Planck Institut für Physik und Astrophysik  
Munich, West Germany

## ABSTRACT

The Conference reviewed what we have learned after one year from SN 1987a. In particular, new information continues to come in daily on the evolving spectra, including x-rays and  $\gamma$ -rays. We now know the light curve was indeed powered by  $^{56}\text{Co}$  decay. The neutrino data from IMB and Kamioka continues to be analysed. It is fit very well by a standard collapse to a neutron star although some nagging problems with the angular distribution remain. Constraints on neutrino and other weakly interacting particle properties have been developed that rival or exceed terrestrial laboratory results. The question of the counts detected by the Mt. Blanc neutrino detector had new mysteries added at this meeting as reports of multiple coincidences with gravitational wave detectors at Maryland and Rome were presented. Future supernova rates were also discussed. It was argued that neutrino detection from a future supernova in our Galaxy might be the only way to prove that the  $\nu_\tau$  was the dominant matter of the Universe.

\* Prepared for the Proceedings of the La Thuile Conference, February 1988

LA Thuile, It. Feb 28 - Mar. 5, 1988

**MASTER**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED



Supernova 1987a has been one of the most exciting scientific events of this century. It has been almost 400 years since a supernova, visible to the unaided eye, has occurred. This one not only was detected in all parts of the electromagnetic spectra but also with neutrinos. The neutrino detection marked the birth of extra solar system neutrino astronomy.

This conference at La Thuile in Italy's Aosta Valley took place almost exactly one year after the discovery of SN 1987a. It addressed the question, what have we learned from this event.

New observations from the Supernova have resolved issues such as the energy source for the light curve (Ni-Co-Fe decay) and the presupernova history of the progenitor (it was once a red giant and ejected its outer envelope to become a blue star). The neutrino observations have now been well studied and understood. Most aspects of the supernova seem to be falling into place very well.

Contrary to the attempt by the popular press to imply mystery, SN 1987a is actually reasonably well understood. In particular, many stellar evolution calculations (c.f. Lamb, Iben and Howard<sup>1</sup>, 1977; Truran and Brunish<sup>2</sup>, 1985) had indicated that massive stars could die with their outer regions as blue rather than red stars either because they were never red or because they were once red but contracted to the blue either by mass loss or simple contraction of the convective zone. Thus the fact that the progenitor was Sanduleak-69 202, a blue supergiant of  $\sim 20M_{\odot}$ , was not surprising. Once it is known to be a compact blue star then the low luminosity naturally follows. (Blue means higher temperatures, thus smaller radius for a given stellar luminosity. Smaller radius at the time of shock breakout yields lower initial supernova luminosity).

The dilemma of whether or not Sanduleak-69 202 was ever red has now been resolved by observations. It has been shown<sup>3,4</sup> that there is a circumstellar shell about 0.7 light years from the progenitor star that is the previously ejected red giant envelope. This shell has been seen in the uv from the reflected supernova light. It is clear that it is the ejected red giant envelope because the surface composition of the supernova was rich in nitrogen as one would expect near the base of a CNO burning envelope. Therefore, mass loss did occur and the progenitor was once red and turned to blue. Such a conclusion further stimulates the question of how frequent is this phenomena of massive red giants losing their envelopes prior to collapse. Mass loss may even be enhanced for the higher metallicity stars of the disk, thus making low luminosity Type II's very common though hard to observe in other galaxies.

Another question that has been resolved by recent observations is the energy source that keeps the light curve so luminous for the whole year. It is now known that the decay of

$^{56}\text{Ni}$  to  $^{56}\text{Co}$  to  $^{56}\text{Fe}$  is the responsible source.<sup>5,6</sup> In particular, nucleosynthesis produces the unstable alpha particle nucleus  $^{56}\text{Ni}$  which decays to  $^{56}\text{Fe}$ . The intermediate daughter  $^{56}\text{Co}$  has a half-life of 77 days which corresponds exactly to the exponential post-maximum light curve decay. Not only does this fit, but the solar maximum mission (SMM) has directly observed 2  $\gamma$ -ray lines characteristic of the  $^{56}\text{Co}$  decay to  $^{56}\text{Fe}$ . Thus we have dramatic proof of fresh nucleosynthesis. In fact, if the  $0.07M_{\odot}$  of freshly synthesized Fe coming from this Type II is true of all Type II's then we have no need for significant numbers of Type I's to produce Fe.<sup>7</sup>

The traditional concerns of Type I vs Type II are only concerns of whether or not hydrogen was present in the outer envelope, and for traditional Type II's it has to be spread out in red giant form.<sup>8</sup> The real physics question is whether the star was massive enough to undergo core collapse or whether the explosion was caused by a nuclear detonation (deflagration) of a C-O white dwarf. Collapse yields detectable neutrinos, detonation does not. Thus this was a core collapse, the light curve questions are more analogous to surface weather.

For over 20 years, it has been known that the gravitational collapse events, thought to be associated with Type II supernovae and neutron star or black hole formation, are copious producers of neutrinos. In fact, the major form of energy transport in these objects comes from neutrino interactions. It has long been predicted that the neutrino fluxes produced by these events would be high enough that if an event occurred within the galaxy, it could be detected. The following discussion of the neutrinos borrows heavily from Schramm (1987)<sup>9</sup>.

It has been well established in the models of Arnett<sup>10</sup> and Weaver et al.<sup>11</sup> that massive stars with  $M \gtrsim 8M_{\odot}$  evolve to an onion-skin configuration with a dense central iron core of about the Chandrasekhar mass surrounded by burning layers of silicon, oxygen, neon, carbon, helium, and hydrogen. Collapse inevitably occurs when no further nuclear energy can be generated in the core. The collapsing iron core mass is always about  $1.4 \pm 0.2M_{\odot}$ .

Bethe and Brown<sup>12</sup> and Baron et al.<sup>13</sup> have argued that, provided the equation of state of matter above nuclear density is very soft, stars in the mass range  $10 \leq M \lesssim 16M_{\odot}$  with cores slightly below the  $1.4M_{\odot}$  Chandrasekhar mass may explode due to the prompt exit of the shock wave formed after the core bounces upon reaching supra-nuclear density. For stars with  $16 \lesssim M \leq 80M_{\odot}$ , the shock wave stalls on its exit from the core and becomes an accretion shock. Wilson et al.<sup>14</sup> have shown that such stars will eventually ( $\sim 1$  second later) eject their envelope as a result of neutrino heating in the region above the neutrinosphere and below the shock. (The delayed ejection can also occur in the lower mass collapses if the initial bounce does not produce an explosion.) The success of

such delayed ejection seems to depend critically on the calculational details. Hillebrandt<sup>15</sup> argues that the delayed mechanism may also be sensitive to the equation of state in the collapsing core. Obviously the above scenarios are sensitive to the stiffness of the core equation of state which is still poorly known at and above nuclear mass densities. As was first emphasized by Arnett and Schramm<sup>16</sup>, the ejecta have a composition which fits well with the observed 'cosmic' abundances for the bulk of the heavy elements.

*Regardless* of the details of collapse, bounce, and explosion, it is clear that to form a neutron star the binding energy,  $\epsilon_B \approx 2 \times 10^{53}$  ergs must be released. The total light and kinetic energy of a supernova outburst is about  $10^{51}$  ergs. Thus, the difference must come out in some invisible form, either neutrinos or gravitational waves. It has been shown<sup>17</sup> that gravitational radiation can at most carry out 1% of the binding energy for reasonable collapses because neutrino radiation damps out the non-sphericity of the collapse (see Kazanas and Schramm<sup>18,19</sup>). Thus, the bulk ( $\gtrsim 99\%$ ) of the binding energy comes off in the form of neutrinos.

It is also well established<sup>20</sup> that for densities greater than about  $2 \times 10^{11}$  g/cm<sup>3</sup>, the core is no longer transparent to neutrinos. Thus, as Mazurek<sup>21</sup> first established, the inner core has its neutrinos degenerate and in equilibrium with the matter. For electron neutrinos, the 'neutrinosphere' has a temperature such that the average neutrino energy is around 10 MeV. This was established once it was realized that the collapsing iron core mass is  $\sim 1.4M_\odot$ , due to the role of the Chandrasekhar mass in the pre-supernova evolution fixing the scale. Since the  $\mu$  and  $\tau$  neutrinos and their antiparticles only interact at these temperatures via neutral rather than charged current weak interaction, their neutrinosphere is deeper within the core. Therefore, their spectra are hotter than the electron neutrino. The electron antineutrino opacity will initially be dominated by charged current scattering off protons but as the protons disappear, it will shift to neutral current domination. Thus the effective temperature for  $\bar{\nu}_e$ 's changes from that for  $\nu_e$ 's to that for  $\nu_\mu$  and  $\nu_\tau$ 's.

The average emitted neutrino energy is actually quite well determined (Schramm 1987, ref.3, also ref.15) for the peak of the neutrino distribution and is very insensitive to model parameters. The peak emission occurs at the highest temperature for which neutrinos can still free stream out of the star. The temperature of this peak varies as the  $\sim 1/5$  power of the model dependent parameters thus yielding a well determined value regardless of the input.

For  $\nu_e$  this yields

$$T_{\nu_e} \simeq 3.5 \text{ MeV}$$

or an average energy

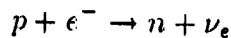
$$\langle E_{\nu_e} \rangle \approx 10 \text{ MeV}.$$

This is in good agreement with detailed numerical results. As mentioned above, for  $\bar{\nu}_e$ 's the average energy increases with time. The time averaged value is about 15 MeV.

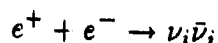
It should also be noted that since the interaction cross sections in the star are proportional to the square of the neutrino energy, the lower energy neutrinos can escape from deeper in the star. In addition, as time goes on the core evolves, so some higher energy neutrinos are able to get out from deeper inside. Thus, the energy distribution of the emitted neutrinos is not a pure thermal distribution at the temperature of the neutrinosphere. Also, particularly for the  $\bar{\nu}_e$ 's where  $T$  changes with time, the time integrated distribution is a superposition of many temperatures so its shape will not be purely Fermi-Dirac. In fact, Mayle et al.<sup>26</sup> argue that the high energy tail of the distribution is above the thermal tail of a distribution which fits the peak.

While the general scenario for collapse events is well established, the detailed mechanism for the ejection of the outer envelope in a supernova as the core collapses to form a dense remnant continues to be hotly debated. Therefore, most theorists working on collapse prior to SN 1987A have focused on these details in an attempt to solve the mass-ejection problem. As a result, most of the pre-1987 papers in the literature are concerned with the role played by neutrinos internal to the stellar core, rather than the nature of the fluxes which might be observed by a neutrino detector on earth. In particular, while it has been known since the early 1970's<sup>24,25</sup> that the average energy of the emitted neutrinos was about 10 MeV, with neutrino luminosities of a few  $10^{52}$  ergs/sec, the detailed nature of the emitted spectra was only recently explored in detail by Mayle, Wilson, and Schramm<sup>26,27</sup>. Their calculation emphasized the high-energy neutrinos which are easier to detect. The diffusion approximation used in most collapse calculations does not treat the high-energy tail of the spectrum accurately.

In addition to the basic energetic arguments, there is the neutronization argument (see ref. 3, and references therein). The collapsing core has  $\sim 10^{57}$  protons that are converted to neutrons via



to form a neutron star. (This process is also called deleptonization by some authors.) Each  $\nu_e$ , so emitted from the core, carries away on the average 10 MeV, thus around  $1.3 \times 10^{52}$  ergs are emitted by neutronization  $\nu_e$ 's. this is  $\lesssim 10\%$  of the binding energy. The remainder of the neutrinos come from pair processes such as



where  $i = e, \mu$ , or  $\tau$ , with  $\nu_\mu$  and  $\nu_\tau$  production occurring via neutral currents, and  $\nu_e$  via both charged and neutral currents. (See review by Freedman et al.<sup>28</sup>.) As an aside, it is curious to note that the neutral current role focused upon in the 1970's was the coherent scattering off heavy nuclei and its possible role in the ejection. These early papers also recognized the neutral current emission of all species but did not emphasize it due to the preoccupation with ejection mechanisms and presumed unlikelihood of ever expecting to see a neutrino burst.

Some fraction ( $\lesssim 50\%$ ) of neutronization occurs as the initial shock hits the neutrinosphere (the remainder occurs on a neutrino diffusion timescale). The pair  $\nu$ 's always come from the 'thermally' radiating core on a diffusion timescale. The timescale for an initial neutronization  $\nu_e$  burst will be much less ( $\lesssim 10^{-2}$  sec) than the diffusion time ( $\sim$  seconds) that governs the emission of the bulk of the flux. Some so-called 'advection/convection' models increase the initial  $\nu_e$  burst by convecting high- $T$ , degenerate core material out. These models have higher-energy  $\nu_e$ 's with larger fluxes, and suppress the  $\bar{\nu}_e$  fluxes.

Even in the "detailed" explosion models, more than half of the thermal neutrino emission comes out in the first one or two seconds with prompt models having even a greater fraction emitted in less time. The remainder comes out over the next few tens of seconds as the hot, newborn, neutron star cools down via Kelvin-Helmholz neutrino cooling to become a standard 'cold' neutron star. Burrows and Lattimer<sup>29</sup> carried out detailed cooling calculations prior to SN 1987A. Most other authors cut off their calculations after the bulk of the neutrino emission occurred and mass ejection was established. Detailed models for the bulk of the neutrino emission (c.f. Mayle et al.<sup>26</sup>) seem to find that the pair processes yield an approximate equipartition of energy in the different species. The  $\nu_\mu$  and  $\nu_\tau$ 's have a higher energy per  $\nu$ , thus their flux is down to preserve this equipartition.

Despite the explosive mechanism, for stars in the mass range  $10 \lesssim M \lesssim 16M_\odot$  the most distinctive structure in the neutrino signal is the initial neutronization burst. However, in the delayed explosions seen by Wilson et al.<sup>21</sup>, for stars with  $M \geq 16M_\odot$ , besides the burst, the neutrino luminosity shows an oscillatory behavior superimposed on an almost constant neutrino luminosity during the post-bounce pre-ejection accretion phase. The oscillations in luminosity are related to oscillations in the mass accretion rate onto the proto-neutron star. The physical nature of the instability that is responsible for the oscillations in luminosity and mass-accretion rate is described in Wilson et al.<sup>21</sup>, and in more detail in Mayle<sup>30</sup>. After the envelope is ejected, the luminosity will smoothly decrease as the remaining binding energy is emitted during the Kelvin-Helmholz cooling. Models without the accretion phase go directly from the neutronization burst to Kelvin-Helmholz

cooling. Those models thus have the  $\bar{\nu}_e$  emission fall off with a single characteristic cooling time. However, models with an accretion phase have a high average emission rate for a second or so after the neutronization burst before the mass ejection and onset at the cooling phase with its dropping emission.

It is important to remember that the average neutrino luminosity, mean neutrino energy, and total emitted energy depend only on the initial iron-core mass and are otherwise independent of the explosive mechanism. Because the opacity is less for the  $\nu_\mu$  and  $\nu_\tau$ 's, they are emitted from deeper in the core where temperature is higher. Thus, they have a higher average energy. The calculations of Mayle et al.<sup>26</sup> find  $E_{\nu_\mu} \simeq E_{\nu_\tau} \approx 2E_{\nu_e}$ . The easier-to-observe  $\bar{\nu}_e$ 's start out with energy comparable to  $\nu_e$ 's and gradually shift over to the  $\nu_\mu - \nu_\tau$  energy as their emission continues from progressively deeper in the core.

By using simple, model-independent arguments, one obtains a crude estimated  $\bar{\nu}_e$  counting rate for an  $H_2O$  detector

$$n = \frac{(1 - f_n)\epsilon_B}{2N_\nu\langle E_\nu \rangle} \frac{\langle \sigma \rangle}{4\pi r^2} \frac{2}{18} \frac{M_D}{m_p} \quad (1)$$

where  $f_n$  is the fraction radiated in the neutronization burst,  $\langle E_\nu \rangle$  is the average neutrino energy,  $\langle \sigma \rangle$  is the average cross section above threshold. [It should be noted that the cross section goes as  $p_e E_e$  not  $E_\nu^2$ , (see discussion Appendix to reference 3). However, this effect can be treated as an additional detector sensitivity factor.]  $r$  is the distance to the LMC  $\approx 50$  Kpc,  $M_D$  is the mass of the detector,  $m_p$  is the proton mass, and  $N_\nu$  is the number of neutrino flavors. (For the Mt. Blanc liquid-scintillator detector, one should multiply by 1.39 for the average number of free protons in  $H_{2+2n}C_n$ .) Using F-D statistics yields

$$\langle \sigma \rangle \approx \frac{\int_{E_c}^{\infty} \bar{\sigma} \frac{E^4 dE}{1 + e^{E/T}}}{\int_0^{\infty} \frac{E^2 dE}{1 + e^{E/T}}} \quad (2)$$

where  $E_c$  is the low-energy cut-off and  $\bar{\sigma} \equiv \sigma/E_\nu^2$ .

Plugging in values yields the expected number of counts  $n$  of

$$n = 5.2 \left( \frac{T}{4\text{MeV}} \right) \left( \frac{\epsilon_B}{2 \times 10^{53}\text{ergs}} \right) \left( \frac{1 - f_n}{0.9} \right) \frac{1}{(N_\nu/3)} \left( \frac{M_D}{\text{ktons}} \right) \left( \frac{50\text{kpc}}{r} \right)^2 \quad (3)$$

For the 2.14 kiloton Kamioka detector, this yields about 10 counts. Similarly, for the Mt. Blanc detector with 0.09 kilotons, times 1.39 extra, free protons in the scintillator, a simple prediction is  $\sim 0.5$  counts. IMB is a little more difficult because its threshold is not below the peak  $\bar{\nu}_e$  counting rate. In addition, it is totally dominated by the high  $T$  tail where a constant  $T$  may not be an ideal approximation. However, we can crudely estimate that  $\sim 50\%$  of the  $\bar{\nu}_e$  counting rate is above the approximate IMB low  $E$  cut-off of 20 MeV. Thus, with 5 kilotons, IMB should roughly get 13 effective counts.

To estimate the expected number of electron scattering events one must do a bit more if threshold effects are to be included. Electron scattering yields a very flat energy distribution. When such a flat energy distribution is combined with a finite temperature F-D distribution for the initial neutrinos, one finds an expected energy distribution for the scattered electrons which is quite peaked at low energies. If pure constant temperature F-D distributions are assumed for the neutrinos, the total number of scattering is expected to be  $\lesssim 0.5$  for  $10\bar{\nu}_e$  capture events. If the high energy tails are suppressed by absorption as Imshennik and Nadyoshen (c.f. 24 and references therein), then the expected scattering rate is even lower. However, if the high energy super-thermal tails of Mayle et al. are included, one finds that for every  $10\bar{\nu}_e$  absorptions, one expects about 0.7 to 1  $\nu_e$  scattering and about 0.7  $\nu_x e$  scattering, where  $\nu_x$  is either  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_\tau$ ,  $\bar{\nu}_\tau$ , or  $\bar{\nu}_e$ . We can understand why the scattering rate is  $\sim 1/15$  even though the cross section ratio at 10 MeV is  $\sim 80$  by remembering that there are five electrons for each free proton in an  $H_2O$  target. In addition, at a given energy from our cross section table

$$(\sigma_{\nu_e^e} + \sigma_{\nu_\mu^e} + \sigma_{\bar{\nu}_\tau^e} + \sigma_{\bar{\nu}_\mu^e} + \sigma_{\bar{\nu}_e^e})/\sigma_{\nu_e^e} \simeq 1. \quad (4)$$

Thus, if fluxes are equal, the rate is doubled. Actually, average energy of other species is about twice that of  $\nu_e$ , but fluxes are reduced accordingly to roughly maintain equipartition of energy per neutrino species, thus keeping scattering constant. The difference in expected number of scatterings is an important probe of the high energy tail.

For the 615-ton  $C_2Cl_4$  Homestake there are  $2.2 \times 10^{30}$   $^{37}Cl$  atoms. As seen from the Appendix to reference 3, the cross section is not a simple integer power of  $E_\nu$ , however, it seems to fall roughly between  $E^3$  and  $E^4$  relationship for  $E_\nu \lesssim 30$  MeV. For temperatures above 5 MeV, the peak contribution to the thermal average would be coming from energies above 30 MeV where the cross section no longer rises as rapidly and the expected counting rate no longer continues to rise with temperature. In the standard case, one expects about a half of a count above the background. However, for advection models, one might expect several  $^{37}Cl$  events. Similar to the solar case,  $^{37}Cl$  is once again a potentially sensitive thermometer. This also constrains models, such as those presented by LoSecco, where high energy  $\nu_e$ 's are dominant in the event.

All the predictions described above assume a simple, spherical symmetric collapse. If large amounts of rotation or magnetic fields were present (with energies comparable to the binding energy) then the standard model would be altered with different time scales and different core masses and binding energies, since such conditions would alter the initial core mass as well as the dynamics. We will see that the Kamioka/IMB neutrino burst fits the standard assumptions well so that the collapse which created that burst did not have significant rotation or magnetic fields.



Before SN 1987A, it was also obvious that a supernova, if detected by its neutrinos, would constrain neutrino properties. In particular, if the neutrinos got here, we'd have a lifetime limit. If the time pulse wasn't too spread out, that would mean a mass limit on those neutrino types that were clearly identified. Also, from the number of  $\bar{\nu}_e$  counts, one could constrain  $N_\nu$  since if  $N_\nu$  was large, the fraction of thermally produced  $\bar{\nu}_e$ 's would go down. In addition, neutrino mixing could be constrained by detecting different types and comparing; with Mikheyev-Smirnov<sup>23</sup> matter mixing, as parameterized to solve the solar neutrino problem,  $\nu_e \rightarrow \nu_\mu$  (or  $\nu_\tau$ ), and  $\nu_\mu$  (or  $\nu_\tau$ )  $\rightarrow \nu_e$ , but nothing happens in the antineutrino sector. Such mixing would eliminate seeing the initial  $\nu_e$  burst, but give higher energies to the later, thermal  $\nu_e$  since they'd be mixed  $\nu_\mu$ 's (see Walker and Schramm<sup>32</sup>). Of course, non-solar Mikheyev-Smirnov can be used if antineutrino mixing is seen. These effects were examined by Dar in his talk.

## NEUTRINO OBSERVATIONS

Table 1 summarizes the neutrino observations, noting two reported neutrino bursts. Before discussing the plausibility of the first event, it is important to note that there clearly was a detection on February 23rd near 7h 35m U.T. at the IMB and Kamioka detectors. Thus, unquestionably *extra solar system neutrino astronomy has been born!* While the smaller detectors also reported counts at this time, it is clear that they would not have interpreted them as anything special if the IMB/Kamioka burst had not been known. Thus while they don't cause any doubts about the existence of this burst they also can't confirm it either. This was discussed at this meeting by Vandevelde and Koshihira.

Let us now examine the burst Mt. Blanc reported on February 23rd, -2:52 with five events which was unsubstantiated by the other three detectors. While lack of concordance is easy to understand for IMB and Baksan, due to their higher thresholds, the lack of a strong concordant signal, significant above background, is difficult with regard to Kamioka. The Kamioka detector is 2140 tons, compared to 90 tons for Mt. Blanc. (Mt. Blanc was designed to detect  $\bar{\nu}_e$ 's from collapses in our galaxy, not the LMC.) Thus, many people have dismissed this first event as an unfortunate statistical accident. *A posteriori* statistics are difficult. While the chance of background exactly duplicating this event configuration eight hours before the visual outburst is low, perhaps the more relevant question is: What is the chance of background producing any plausible signal within two days prior to the visual detection? If any plausible signal is defined as three or more events (only three events were clearly above background) in less than or equal to 30 seconds, a chance occurrence becomes quite reasonable and many have assumed this explanation. In fact, Savaadra in his talk mentioned that in nine months the Mt. Blanc detector did indeed have another 5

event burst as would be reasonable given the poisson statistics. However, one should be cautious in following popular opinion too rapidly. Detections near threshold can be tricky, and statistics of small numbers are notoriously suspect. In fact, while both thresholds are indeed low, Mt. Blanc is lower. In particular, Mt. Blanc sees positrons down to  $\sim 5$  MeV whereas Kamioka does not see positrons below 7 MeV (their 50% efficiency point is actually 5 MeV). Furthermore, Mt. Blanc sees total energy including  $e^+e^-$  annihilation thus it is capable of detecting incoming neutrinos down to 5.3 MeV whereas Kamioka must add 1.3 MeV to get their neutrino energies, yielding their lower bound on detectable neutrinos of 8.3 MeV, a full 3 MeV above Mt. Blanc.

Kamioka did report that they had a background count above threshold in the 10-minute interval centered at the Mt. Blanc event which is consistent with their background. They have also examined their sub-threshold background and found no evidence for enhancement.<sup>60</sup> Figure 1 shows the implied temperature and neutrino luminosity implied by the Mt. Blanc. These were estimated by deconvoluting F-D distributions with thresholds and efficiencies. Notice that the burst reported at Mt. Blanc is not well fit by the standard collapse assumptions but instead requires lower-than-expected temperatures and extraordinarily high total energies. Let us suspend our theoretical prejudice and ask if such a high-luminosity, low- $T$  event did occur, could Kamioka not have seen it? In fact, as first noted by De Rujula<sup>33</sup> a minimal Kamioka detection cannot be totally excluded because the implied Mt. Blanc burst temperature is so low, and the thresholds are different. Even zero events is possible if the temperature of the neutrino distribution were low enough. The lower part of Figure 1 shows the expected Kamioka counts versus temperature of the source for the Mt. Blanc burst. To get less than a few counts at Kamioka requires neutrino temperatures under 1 MeV. Lower temperatures yield higher flux in order to get 5 events at Mt. Blanc. To avoid a Kamioka conflict would require  $T \leq 1$  MeV and  $E_{TOTAL} \gtrsim 10^{55}$  ergs! Comparable to or greater than the entire rest mass of the Sanduleak star. Models with large magnetic fields and/or rotation, such as Sybalistiy et al.<sup>34</sup> have low temperatures, but it is hard to imagine an event which radiates a *minimum* of several neutron star *rest masses* in neutrinos, or has a very non-thermal distribution. The non-standard event must then be followed by a subsequent collapse five hours later to a black hole or a dense, strange-matter star looking very much like a normal collapse, as we shall see.

### GRAVITATIONAL WAVE COINCIDENCE?

One of the most surprising results presented at this meeting was the possible coincidence of 11 Mt. Blanc events around 2 hours of the 5 event burst which were in simultaneous coincidence with the Rome and Maryland gravity wave detectors. These

are room temperature bar detectors. Thus by the standard estimates of sensitivity they would have required several  $10^3 M_\odot$  of energy in gravity waves at the LMC to produce a detection. However, Weber disputed the standard gravity cross section estimates which would, if valid, remove that energetic problem. An alternative approach by DeRujula was to accept the standard estimates but argue that some new scalar field produced the gravity wave detections. Even if we go to new physics to explain the gravity waves or accept Weber's dismissal of that problem, we are still left with the problem of how to get the Mt. Blanc detector to "fire." While it is difficult to see how any 2 hour sequence could occur which would be coupled to a collapse that has intrinsic timescales of seconds or less, the real problem is again energetics of the Mt. Blanc detections. If 5 events cause energetic problems, think of what 11 do. An alternative is that these events were not in the LMC but *much* closer, thus reducing the energy requirements but requiring a remarkable timing coincidence. Given all these problems, we still quote Eddington: "Observations should not be believed until confirmed by theory". Unlike Kamioka and IMB, it should be remembered that the Mt. Blanc detector was actually constructed to look for collapse neutrinos; unfortunately it was optimized for collapses within 10 kpc.

Let us now turn our attention to the well established Kamioka/IMB burst. (For a detailed discussion, the fact that Mt. Blanc and Baksan also have signals is irrelevant other than to show that detectors  $\sim 1/20$  the mass can have  $\sim 1/10$  the counts, due to statistics of small numbers plus possible background subtraction uncertainties.) Figure 2 is a plot showing the energy and timing of the Kamioka and IMB events. (Kamioka's event no. 6 is ignored as being below their criteria for a definitive event.) Note that almost all the counts concentrate in the first few seconds, as one expects in collapse models. A reasonable tail, as predicted by theory<sup>26,34</sup>, yields low but finite rates after ten seconds. Such rates following the bulk early emission from an accretion phase have little difficulty in producing apparent gaps in counts due to the problems of small number statistics (c.f. Bahcall<sup>35</sup> et.al. or Mayle and Wilson<sup>36</sup>). Note also that the IMB late counts (dashed lines) nicely fill in the 6 second gap in the Kamioka data.

To examine consistency let us use the number of counts and mean energies measured in the experiments to determine the implied temperature and energy emitted in  $\bar{\nu}_e$ 's. Such estimates require detailed consideration of efficiency and threshold effects.

To convert a mean neutrino energy to an effective temperature requires assuming that the emitted  $\nu$  spectrum was well described by Fermi-Dirac statistics. Mayle et al. argue that this is a reasonable assumption, however, as mentioned before, they did find that their models had a higher tail at high energies than a simple, single-temperature model would yield. Thus, one might expect the IMB temperature to be slightly higher than the Kamioka

temperature due to its weighting on the high-energy events. If the  $\nu$ 's fit F-D statistics, then the mean energy  $\langle E_\nu \rangle$  as recorded by a detector with cross section proportional to  $E_\nu^2$  and cut-off energy  $E_0$ , with efficiency of detection  $f(E)$ , is given below, where  $E$  and  $T$  are measured in the same units, and  $E_0 = E_c(e^+) + Q$

$$\begin{aligned} \langle E_\nu \rangle &= \frac{\int_{E_0}^{\infty} \frac{f(E)E^5 dE}{1+e^{E/T}}}{\int_{E_0}^{\infty} \frac{f(E)E^4 dE}{1+e^{E/T}}} \\ &\simeq \frac{E_0 + 5T + 20\frac{T^2}{E_0} + \frac{60T^3}{E_0^2} + \frac{120T^4}{E_0^3} + \frac{120T^5}{E_0^4}}{1 + \frac{4T}{E_0} + \frac{12T^2}{E_0^2} + \frac{24T^3}{E_0^3} + \frac{24T^4}{E_0^4}} \end{aligned} \quad (5)$$

which goes to the well known F-D integral values for  $E_0 = 0$ . Thus, we have a polynomial equation for  $T$ :

$$\begin{aligned} T^5 + \left(E_0 - \frac{\langle E_\nu \rangle}{5}\right) T^4 + \left(\frac{E_0^2}{2} - \frac{\langle E_\nu \rangle E_0}{5}\right) T^3 + \left(\frac{E_0^3}{6} - \frac{\langle E_\nu \rangle E_0^2}{10}\right) T^2 \\ + \left(\frac{E_0^4}{24} - \frac{\langle E_\nu \rangle E_0^3}{30}\right) T + \frac{E_0^5 - \langle E_\nu \rangle E_0^4}{120} = 0 \end{aligned} \quad (6)$$

This latter equation can be trivially solved for the effective temperature,  $T_{\nu_e}(\langle E_\nu \rangle, E_0)$ : from this equation it is obvious that the effective  $T$  is a very sensitive function of  $E_0$ . We will use efficiency weighted values for  $n$  so as to avoid the treatment of the efficiency function in the integrals. Evaluating  $\langle \sigma \rangle$  counts and energies from equation 5 yields

$$\langle \sigma \rangle \approx \frac{7.5 \times 10^{-44}}{2} T_{\nu_e}^2 \left( \frac{E_0^4}{2T^4} + \frac{2E_0^3}{T^3} + 6\frac{E_0^2}{T^2} + 12\frac{E_0}{T} + 12 \right) e^{-E_0/T} \text{cm}^2 \quad (7)$$

again, a function that is sensitive to  $E_0$ . Equation 3 for  $n$  can be inverted to solve for  $\epsilon_{\nu_e}$ , where the total energy,  $\epsilon_T$  (which can be compared to neutron star binding energy,  $\epsilon_B$ ) is related to  $\epsilon_{\nu_e}$  by

$$\epsilon_T \approx \frac{2N_\nu \epsilon_{\nu_e}}{(1 - f_n)}.$$

The numbers in Figure 3 are calculated assuming  $N_\nu = 3$  and  $f_n = 0.1$ , with Kamioka having  $M_D = 2.14$  kilotons, and IMB having  $M_D = 5$  kilotons. Figure 3 shows the energy radiated versus  $T_{\nu_e}$ . The boundaries of the region come from one  $\sigma$  errors in counts as well as the range of reasonable assumptions one might make about cut-off energies and stated experimental errors in energy.

While one might expect (from Mayle et al.) IMB to measure a slight higher  $T$ , it is interesting that there is nevertheless a region of overlap where both data sets yield the same  $T_{\nu_e}$  and  $\epsilon_{\nu_e}$ . It is particularly satisfying that this region of overlap is exactly where one might have expected a standard gravitational collapse event to plot, namely,

$\epsilon_T \sim 2 \times 10^{53}$  ergs,  $T \sim 4.5$  MeV. Similar conclusions were reached by Sato and Suzuki<sup>37</sup> and Bahcall et al.<sup>35</sup> using a different treatment than has been applied here. Once  $T$  and  $\epsilon_T$  are determined one can use the luminosity-temperature relationship to solve for the radius,  $R$ , of the neutrinosphere and obtain, in our case, a few tens of kilometers in reasonable agreement with the standard models, whether or not the first two or the last three events from Kamioka are included. It is worth noting that the above analysis is very crude, Kolb et al.<sup>38</sup> have pointed out that simple converting of  $E_e$  to  $E_\nu - Q$ , as was done here, is inaccurate although it does not effect these conclusions. Also note that the boundaries used in Figure 3 do not have a quantitative statistical meaning since systematic as well as statistical uncertainties were mixed in obtaining them. Nonetheless, the results are suggestive and more detailed analyses seem to yield similar conclusions<sup>35,36,37</sup>.

The angular distribution for Kamioka used to show an excess of 3 or so counts in the direction of the LMC with a possible slight excess in the direction of LMC. However, at the Yamada Meeting in Tokyo, it was revealed that the angular direction for the #2 event was in error and should be  $40^\circ$  not  $18^\circ$ . This gives an excess of only 2 over isotropic. This also eliminates the use of the 2 events for mixing arguments, etc. as Dar proposed. Since  $\bar{\nu}_e + p$  would yield an isotropic distribution, the number of directed electron scattering events should be relatively small, as might be expected by the ratio of cross sections. As mentioned before Mayle et al.<sup>26</sup> expect  $\sim 1.5$  for  $12M_\odot$  or 2 for their  $15M_\odot$  model in reasonable agreement with the observations. One also expects that  $\sim 50\%$  of these scattering events are higher energy  $\nu_\mu$ ,  $\nu_\tau$ ,  $\bar{\nu}_\mu$ ,  $\bar{\nu}_\tau$ , or  $\bar{\nu}_e$  events. This also fits well since the highest energy Kamioka events have  $\cos \theta > 0.7$ . It is also intriguing that the first event had  $\cos \theta$  closest to unity. Remember that the initial 0.01 sec neutrino burst is expected to be  $\nu_e$ 's with no  $\bar{\nu}_e$ 's. While such a scattering might be excessive considering the cross section suppression (unless the  $\nu_e$  flux is slightly enhanced by advection convection) statistics of one are not worth arguing about and are not useful in confirming or denying one theory instead of another. It is interesting to note that models with no high energy tail would predict less than 1/2 a scattering event. Since the data seems to require 1 or more with 2 as a best fit, it is reasonable to argue that the data do lean towards models with high energy tails over models with pure constant  $T$  distributions and certainly models with absorption suppressed tails run into difficulty. However, statistics of 2 do not make a strong case.

The angular distribution for IMB is more problematic.<sup>62</sup> Initially the failure of one of the 4 power supplies was thought to bias the data but subsequent analysis showed that the effect was not significant. The IMB distribution peaks at  $\sim 45^\circ$  with most of the events forward and no significant backward scattered events. It clearly is not fit by an isotropic source however if it is recognized that at high energy and with the particular

detector then  $\bar{\nu}_e + p$  should yield  $\sim 1 + 0.2 \cos \theta$  not isotropic and with a high E tail giving  $\sim 1$  e-scattering then the distribution is at a  $\sim 10\%$  probability, so it is not too ( $\lesssim 2\sigma$ ) unlikely (the  $1 + 0.2 \cos \theta$  distribution by itself is at  $< 3\%$  probability level). However, the alternative proposed by Vandevelde of some new physics cannot be trivially excluded, especially when one notes the other mystery of these detectors—namely the suppressed  $\mu/e$  ratio in atmospheric neutrino events.

While discussing  $\nu_e$  scattering, it's worth noting that the  $^{37}\text{Cl}$  experiment of Davis was operating at the time of The Supernova, and counting began shortly after the light was observed. This experiment is only sensitive to  $\nu_e$ 's. After 45 days of counting, Davis saw one count, completely consistent with his normal counting rate<sup>39</sup>. As mentioned before, for a standard collapse one expects from the LMC event  $\sim 0.5$  events in the Homestake Chlorine detector. However, if one interprets the Kamioka data as implying a large excess<sup>40</sup> of  $\nu_e$ 's, then one might have expected several  $^{37}\text{Cl}$  counts. The lack of observed  $\text{Cl}$  counts argues that the  $\nu_e$  flux is not in disagreement with standard predictions of  $\sim 2 \times 10^{52}$  ergs of neutronization  $\nu_e$ 's, plus  $3 \times 10^{52}$  ergs of thermal  $\nu_e$ 's, all at  $E_\nu \sim 10$  MeV ( $T_\nu \sim 3.5$  MeV). This constrains models<sup>41,42</sup> with 'advection' producing excessively large high-energy  $\nu_e$  fluxes and reducing the  $\bar{\nu}_e$  fluxes. As mentioned earlier, such models can predict at most about 5  $^{37}\text{Cl}$  counts. While extreme models with  $T_\nu \gtrsim 5$  MeV and  $f_\nu \sim 1$  may be in difficulty, intermediate models with  $T_\nu \lesssim 4$  MeV and/or  $f_\nu \lesssim 0.5$  are still allowed, as Dar noted

Another constraint on  $\nu_e$ 's comes from interactions with  $^{16}\text{O}$  which would be backward peaked at high energy. No data shows any evidence for this.

The total time spread of the IMB/Kamioka events (see Figure 2) shows that  $\nu$ -emission (or at least detection) lasted for  $\sim 10$  sec. The duration of neutrino emission varies in different collapse models due to the equation of state and the total mass of the collapsing core (is it slightly greater or less than  $1.4M_\odot$ ?) and the dynamics (prompt vs. accretion). Longer timescales favor soft equations of state higher core masses ( $1.4 - 1.6$  vs.  $1.2 - 1.3M_\odot$ ) and thus favor accretion versus prompt mechanisms. However, until we have a collapse in our Galaxy with a more detailed time evolution of the  $\nu$ -signal it will be hard to make detailed statements on the collapse mechanism.

## CONSTRAINTS ON NEUTRINO PHYSICS

Independent of detailed collapse models, we can use the detection of neutrinos from SN 1987a in the Kamioka and IMB detectors to constrain neutrino properties. This was reviewed by Dar<sup>61</sup> and my arguments here parallel but do not exactly replicate his.

## Neutrino Lifetime

Obviously, if  $\bar{\nu}_e$ 's made it over 50 Kpc, they must have a lifetime  $\tau$  such that

$$\gamma\tau \gtrsim 1.6 \times 10^5 \text{ yr}$$

where  $\gamma$  is the relativistic factor ( $\gamma = E_\nu/m_\nu$ ). Of course, to have decay requires  $m_\nu > 0$ . Since  $\gamma$  for  $\nu$ 's from the sun is  $\sim 1/10$ ,  $\gamma$ 's from supernovae (assuming  $m_{\nu_e} = m_{\bar{\nu}_e}$ ) this means that neutrino decay is not a solution to the solar neutrino problem unless one combines decay with special mixing assumptions<sup>43</sup>.

## Decay

An additional lifetime constraint comes for any neutrino decaying to photons. In particular if the decay occurred in the star it would effect the dynamics (Falk and Schramm 1977) as long as  $\gamma \gtrsim 10^{-3}$  sec. Even if it occurred in flight it would yield  $\gamma$ -rays associated with the neutrino burst at unacceptable levels. (SMM saw no  $\gamma$ 's at a level at  $1/\text{cm}^2$  sec and yet there were  $\sim 10^{10} \nu$ 's/ $\text{cm}^2$  sec.) Thus we know that  $\nu_e$ 's  $\nu_\mu$ 's and  $\nu_\tau$ 's are able to go for  $1.6 \times 10^5$  years without decaying to  $\gamma$ 's or to  $e^+e^-$  pairs whose annihilation in space would produce observable  $\gamma$ 's. Turner and Kolb quantify this as  $(\tau/M)_\nu \gtrsim 5 \times 10^{16}$  sec/eV.<sup>63</sup>

## Neutrino Mass

Since the neutrino bursts were relatively narrow in timespread, despite the energies being spread out over a range of about a factor of two, it is obvious that there cannot be too significant of a neutrino rest mass. While the relationship between mass, timespread and energy is derived in freshman physics the world over, the key here is to decide which counts to use to get the time and energy spread, and to estimate what the intrinsic spread was in the neutrino burst in the absence of finite masses. It is these assumptions that have yielded more neutrino mass preprints than neutrino events observed. (Thus, we will not bother to reference them.)

Before discussing what we can say in a model-independent manner, it is important to emphasize that all we get model-independently is an upper limit on the mass, since it is certainly possible that the timespread is just due to intrinsic emission time, and not any mass effects. Thus, all papers claiming finite masses rather than upper limits are intrinsically model-dependent. In addition, since most, if not all, of the counts are  $\bar{\nu}_e$ 's, it is only reasonable to measure neutrino-mass limits for  $m_{\bar{\nu}_e} = m_{\nu_e}$ , not for any other neutrino species unless assumptions about mixing are made. (Of course anything else, like a fine-tuned photino, that interacts in  $H_2O$  with a rate similar to  $\bar{\nu}_e$ , and is produced in supernovae, would also be limited.)

Let us now plug some values into the standard relation for the mass implied by two particles of energy,  $E_1$  and  $E_2$ , emitted at the same time, but arriving 50 Kpc away with a separation  $\Delta t$ .

$$m = 20\text{eV} \left( \frac{E_1}{10\text{MeV}} \right) \left[ \frac{(\Delta t/10\text{sec}) (E_2/E_1)^2}{(r/50\text{Kpc}) (E_2/E_1)^2 - 1} \right]^{1/2}$$

Model-independently, the simplest thing to do is to assume that the entire 13 sec spread of Kamioka was due to this effect. (IMB, with its higher energies, isn't able to constrain things as well.) Schramm<sup>9</sup> and Kolb et al.<sup>38</sup> argue that with these assumptions alone it is really difficult to get limits much better than  $m_{\bar{\nu}_e} \lesssim 30\text{eV}$ . Once we admit that the supernova limit is comparable to the Zurich experimental limit<sup>44</sup> of  $m_{\nu_e} < 20\text{eV}$ , the whole game becomes irrelevant, except for the curiosity that by having the supernova take place in LMC, the values come out very close to terrestrial laboratory measurements.

Alternative games of assuming two or more neutrino types of different mass run into the problem of low cross section for detection of all but  $\bar{\nu}_e$ . In addition, if the three late Kamioka events were a different neutrino with  $m \sim 20\text{eV}$ , compared to the earlier burst with  $m_{\bar{\nu}_e} \ll 20\text{eV}$ , one also has trouble understanding why these late events don't show any strong directional character, since they would then be electron-scattering events for either a  $\nu_\mu + \bar{\nu}_\mu$  or  $\nu_\tau + \bar{\nu}_\tau$ . While it would be wonderful to have  $m_{\nu_\tau} \approx 20\text{eV}$ , to give us the hot dark matter of the universe, this supernova cannot be used to prove it (or disprove it). However, a supernova in our galaxy may provide the only way of measuring a  $\nu_e$  mass of this magnitude.

If specific reasonable models are assumed, slightly tighter limits can be obtained. For example, Abbott, De Rujula and Walker<sup>45</sup> using a diffusing neutrinosphere model obtain a 95% confidence limit of  $m_{\bar{\nu}_e} \lesssim 18\text{eV}$  for the Kamioka events and Bahcall and Spergel<sup>46</sup> find  $m_{\nu_e} \lesssim 16\text{eV}$  if all 19 events are used and the relative timing of Kamioka and IMB is optimized. However Mayle and Wilson<sup>36</sup> show that their models fit the data equally well with any  $m_{\bar{\nu}_e} \lesssim 30\text{eV}$ !

### Number of Neutrino Flavors, Axions and Majorons

A limit to the number of neutrino flavors (with  $m_\nu \lesssim 10\text{MeV}$ ),  $N_\nu$ , can be derived<sup>47,9,48</sup> from observation of the supernova-produced  $\bar{\nu}_e$ 's. The argument is based on the fact that in an equipartition of emitted neutrino luminosities among all flavors, the more flavors, the smaller the yield per flavor. Since  $\bar{\nu}_e$  is only one flavor, this means that a detection of  $\bar{\nu}_e$ 's tells you immediately that the dilution by flavor could not have reduced the luminosity of  $\bar{\nu}_e$ 's below detectability. From these arguments with appropriate uncertainties considered, Schramm<sup>47</sup> showed that the supernova requires  $N_\nu \lesssim 7$ . This number is not as restrictive as cosmological bounds<sup>49,50</sup> but is comparable to current accelerator limits<sup>51</sup>.



This argument can be used to limit any other sort of particle that might be emitted by the supernova and dilute the  $\bar{\nu}_e$  energy share. Using the fact that axions can escape from the higher  $T$  central core even though neutrinos cannot, we<sup>52</sup> can further restrict axion coupling,  $f_a \gtrsim 10^{11}$  GeV exceeding current red giant limits<sup>53</sup> but not eliminating axions altogether since cosmological density arguments could still allow an axion to be the dark matter. In fact, the only axions allowed are ones which would provide interesting cosmological densities.

### Neutrino Mixing

If neutrino mixing occurs between emission and detection, it can obviously alter things. If the mixing is simple vacuum oscillations and the mixing length is short compared to 50 Kpc, then the chief effect will be an increase in the average  $\nu_e$ , and to a lesser extent  $\bar{\nu}_e$ , energy, due to the oscillations with the higher energy  $\nu_\mu$ 's and  $\nu_\tau$ 's. Since we only reliably detect  $\bar{\nu}_e$ 's, this energy enhancement would be difficult to resolve. While some supernova models may need such enhancements to understand the IMB counts, others such as Mayle et al. do not; thus, no definite statements on mixing can occur. (The possibility of the electron scattering events having high energy is also still in the noise.)

Let us now address the matter mixing such as Mikheyev and Smirnov, and Wolfenstein<sup>23</sup> (MSW) have proposed. Walker and Schramm<sup>32</sup> have applied this to stellar collapse scenarios. If this is indeed the solution to the solar neutrino problem, then only  $\nu_e \leftrightarrow \nu_\mu(\nu_\tau)$  mixing is possible, not  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu(\bar{\nu}_\tau)$ . Thus, the solar neutrino solution would not enhance  $\bar{\nu}_e$  fluxes. It would deplete the initial neutronization burst. Since  $\nu_\mu$  cross sections are down by  $\sim 1/6$ , the possibility of seeing a neutronization scattering is significantly reduced. Thus, if the initial possible scattering is real, standard adiabatic MSW is not the solution to the solar neutrino problem. However, proving that the first event in an eleven event distribution is really scattering rather than isotropic background is fraught with statistical difficulties.

If we drop the solar neutrino solution and go to general MSW mixing, then we can mix  $\bar{\nu}_\mu(\bar{\nu}_\tau)$  into  $\bar{\nu}_e$ , which might enhance the energy slightly, but would otherwise do little. No effect would occur for the electron scattering  $\nu_e$ 's. As in the case of vacuum oscillations, no definitive statement can be made.

### COLLAPSE RATES

Over the last 1000 years there have been only 5 visual supernovae in the Milky Way Galaxy, implying at first glance a rate of 1/200 years. However, if we look at galaxies like our own, that is standard evolved spiral Sb and Sc galaxies, we find<sup>10</sup> in other galaxies rates of 1/15 to 1/20 years. Obviously our galaxy's observed low rate is probably the

result of most of our galaxy being obscured from view by dust in the disk. In fact the 5 historical supernovae were all in our sector of the galaxy implying a minimal enhancement of a factor of 5 to  $1/50$  yr to include the entire disk volume. Now that we can detect collapses by neutrinos alone, we don't need to worry about the obscuration of our disk, so the rates in other galaxies where we sample their entire disk might be more relevant. However with neutrino detectors we only see Type II supernovae thus the rates quoted may be on the high side since these include all types ("neutrinoless" Type I's account for  $\sim 1/3$  to  $1/2$  of the supernovae by such direct counting of supernovae in these galaxies). Such direct counting of supernovae is fraught with uncertainties. For example SN 1987A would probably not have been included since it was so underluminous. If the fraction of blue star collapsing is only minimally related to metallicity then SN 1987A types could enhance the supernova for the high metallicity disk populations. It may even be that metallicity enhances the blue progenitor fraction as high mass loss rates might move more stars from red to blue prior to collapse. Of course, if the blue progenitors only occur in metal poor populations, SN 1987A would not alter the statistics for the Milky Way. Similarly, other underluminous collapses, such as Cassiope A would not be detected in extragalactic surveys. Tammann<sup>55</sup> discusses many other difficulties. People have also tried to use pulsar formation rates supernova remnant statistics but these are plagued with uncertainties such as distances, beaming fractions, remnant lifetimes, etc. and can at most give order of magnitude estimates.

An alternative approach to direct searches is to do statistics on stellar types. As mentioned before<sup>7</sup> we don't need Type I's to make iron. Thus apparent large numbers of Type I's may be a selection effect due to their greater brightness or a recently high rate having little to do with the integral rate over the history of the Universe since otherwise Type I's would have produced too much iron. Bahcall and Piran<sup>54</sup> have shown that the rate of formation of all stars  $\gtrsim 8M_{\odot}$  is  $\sim 1/8$  yr using a Salpeter mass function and a constant star formation rate. All such stars presumably undergo collapse. Of course the Salpeter mass function is probably most uncertain for these more massive stars, and the assumption of a constant rate can be argued.

We do not know that from the 2% heavy element content of our galaxy and the assumption that  $\gtrsim 1M_{\odot}$  of heavies is ejected per collapse that the  $10^{11}M_{\odot}$  disk requires  $\lesssim 2 \times 10^9$  ejections over the  $15 \times 10^9$  yr history of the galaxy. Thus our average Type II rate<sup>59</sup> is  $\lesssim 1/7$  yr. Since our current rate of explosion is  $\lesssim$  the average, this is certainly a good limit. Since some galactic evolution models seem to have roughly constant nucleosynthesis rates<sup>56</sup> this limit is also not a bad estimate and is in good agreement with the Salpeter rate estimate. Of course other galactic evolution models argue for high initial supernova rates

which would yield very low present collapse rates to fit the average of  $\sim 1/\text{yr.}$ ; now that we know that SN 1987a was changed from red to blue by mass loss, it is not unreasonable to think that many SN are missed in external surveys. Thus the nucleosynthesis rates and massive star formation rates implying SN rates of  $\sim 1/10$  yr may be reasonable.

### SUMMARY

This supernova in the LMC has proven to be one of the most exciting astrophysical events of the century. It has already taught us much about supernova physics and more should be forthcoming as heavy element spectra and the remnant come into view. We now know that blue as well as red stars collapse, and that SN luminosities for blue progenitors are indeed lower than for red ones.

The neutrinos from SN 1987A have proven that our understanding of the basic energetics of gravitational collapse was quite reasonable once we included neutral current effects. Given that we now know what a neutrino burst looks like, we should have confidence that if a collapse occurs anywhere in our galaxy, regardless of the visibility of the SN, we should observe it.

### ACKNOWLEDGEMENTS

I would like to acknowledge useful conversations with David Arnett, Gene Beier, Adam Burrows, John Ellis, Josh Frieman, Bruce Fryxel, Wolfgang Hillebrand, Rocky Kolb, Toshi Koshiha, Al Mann, Ron Mayle, Keith Olive, Bill Press, Olga Radnyaskaya, Alvaro De Rujala, Richard Schaefer, David Spergel, Albert Stebbins, Leo Stodolsky, Michael Turner, Jim Truran, Jack Vandervelde, Terry Walker, Joe Wampler, and Jim Wilson. This work was supported in part by NSF at the University of Chicago and by the DoE and by the NASA at Fermilab. This manuscript was prepared while the author was supported by the Alexander von Humboldt Foundation at the Max Planck Institut für Physik and Astrophysik in Munich and Garching.

Everyone at this conference is very grateful to the autonomous region of Aosta and the local organizing committee for providing such marvelous surroundings and such a timely event.

## REFERENCES

1. Lamb, Iben, Howard (1977)
2. W. Brunish and J. Truran, *Astrophys. J. Suppl.* **49**, 447 (1985)
3. N. Panageia, 1988 talk presented at the Aspen Supernova Conference.
4. J. Wampler, 1988 talk presented at the La Thuille Supernova Conference.
5. S. Woosley, 1988 UC Santa Cruz preprint and references therein.
6. IAU Telegram, 1987, Solar Maximum Mission
7. W. D. Arnett, J. Truran and D. Schramm, 1988 University of Chicago preprint.
8. J. Danziger, Talk presented at La Thuille.
9. D. Schramm, *Comments Nuc. Part. Phys.* (1987)
10. W.D. Arnett, in *Explosive Nucleosynthesis* (University of Texas Press, Austin, 1973).
11. T. Weaver and S. Woosley, *Proc. Wilson Symposium*, ed. J. Centrella (1983).
12. H. Bethe and G. Browne, *Scientific American* **252**, 60(1985).
13. E. Baron, et al., *Phys. Rev. Lett.* **55**, 126(1985).
14. J. Wilson, et al., *Ann. N.Y. Acad. Sci.* **262**, 54(1975)
15. W. Hillebrandt, Talk given in Tokyo, 1988.
16. W.D. Arnett and D.N. Schramm, *Astrophys. J. Lett.* **184**, L47(1973); S. Woosley, et al., *Astrophys. J. Lett.*, submitted(1987).
17. S. Shapiro, in *Gravitational Radiation*, ed. L. Smarr (Oxford University Press, Oxford, 1978).
18. D. Kazanas and D.N. Schramm, *Nature* **262**, 671(1976).
19. D. Kazanas and D.N. Schramm, *Astrophys. J.* **214**, 819(1977).
20. D.Z. Freedman, D.N. Schramm and D. Tubbs, *Ann. Rev. Nucl. Sci.* **27**, 167(1977); and references therein.
21. T. Mazurek, *Astrophys. J. Lett.* **207**, L87(1976).
22. D.N. Schramm, in *Proc. 2nd Dumband Symposium* p. 87(1976).
23. S.P. Mikheyev and A.Yu. Smirnov, *Il Nuovo Cimento* **9C**, 17(1986); L. Wolfenstein, *Phys. Rev. D* **17**, 2369(1978).
24. D. Schramm and W.D. Arnett, *Astrophys. J.* **198**, 629(1974).
25. J. Wilson, *Astrophys. J.* (1981).
26. R. Mayle, J. Wilson and D.N. Schramm, *Astrophys. J.*, in press(1987).
27. D.N. Schramm, J. Wilson and R. Mayle, in *Proc. 1st International Conference on Underground Physics*, in *Il Nuovo Cimento* **9C**, 443(1986).
28. A. Pomansky, *Proc. XXIIInd Recontre de Moriond*, in press(1987).
29. A. Burrows and J. Lattimer, "The Birth of Neutron Stars", preprint(1985).
30. R. Mayle, Ph.D. Thesis, University of California, Berkeley (available as Lawrence Livermore preprint UCRL 53713).
31. Chechetkin, et al., in *Supernovae*, ed. D. Schramm (D. Reidel, Dordrecht, 1977).
32. T. Walker and D.N. Schramm, *Phys. Lett. B*, submitted(1987).
33. A. de Rujula, CERN preprint TH4702(1987).
34. A. Burrows and J. Lattimer, *Astrophys. J.* **307**, 178(1985).
35. J. Bahcall, T. Piran, W. Press and D. Spergel, IAS preprint(1987).
36. R. Mayle and J. Wilson, Livermore preprint(1987).
37. K. Sato and H. Suzuki, Tokyo preprint UTAP-52(1987).
38. E.W. Kolb, A. Stebbins and M.S. Turner, *Phys. Rev. D*, in press(1987).
39. R. Davis, private communication.
40. J. Arafune and M. Fukigita, Kyoto preprint RIFP-693(1987).
41. A. Burrows, University of Arizona preprint(1987).
42. W.D. Arnett, University of Chicago preprint(1987).
43. J. Frieman and K. Freese, SLAC preprint(1987).
44. A. Kundig, *Proc. XXIIInd Recontre de Moriond*, in press(1987).
45. L. Abbott, A. de Rujula and T.P. Walker, Boston University preprint(1987).
46. J. Bahcall and D. Spergel, IAS preprint (1987).

47. D.N. Schramm, in *Proc. XXIIInd Rencontre de Moriond*, in press(1987).
48. J. Ellis and K. Olive, CERN preprint UMN-TH-605/S7(1987).
49. J. Truran and A. Cameron, *Astrophys. Space Sci.* **14**,179 (1971).
50. I. Danzinger, R. Fosbury, D. Alloin, S. Christiani, J. Dachs, C. Gouffes, B. Jarvis and K. Sahu, *Astron. Astroph.*, in press (1987).
51. Blanco et al. (1987).
52. R. Mayle, J. Wilson, J. Ellis, K. Olive, D. Schramm and G. Steigman, *Phys. Lett. B* (1988)
53. D. Dearborn, D. Schramm and G. Steigman. *Astrophys. J.* **302**, 35(1985).
54. J. Bahcall and T. Piran, *Ap. J.*, (1985); M. Turner, *Phys. Rev. Lett.* (1988); D. Seckel and G. Refelt, *Phys. Lett. B* (1988).
55. G. Tamman in Supernovae Ed. D. Schramm. (Reidel 1977).
56. K. Hainebach and D. Schramm *Astrophys. J.* (1976).
57. Hirata et al. *Phys. Rev. Lett.* **58**, 1490 (1987).
58. Bionta et al. *Phys. Rev. Lett.* **58**, 1494 (1987).
59. D. Schramm *Proceedings SLAC Summer School* (1987).
60. A. Mann, 1988 presented at Aspen Suprnova Conference.
61. A. Dar, 1988 - in Proceedings of this Conference.
62. c.f. J. Vandervelde, 1988 - in Proceedings of this Conference and J. LoSecco - in Proceedings of this Conference, 1988.
63. M. Turner and E. Kolb, 1988 FNAL preprint.

## FIGURE CAPTIONS

Figure 1: The Mt. Blanc event implications on emitted energy temperature and expected Kamioka counts.

Figure 2: The  $\nu$  counting rates for IMB/Kamioka.

Figure 3: Emitted energy,  $\epsilon_{\bar{\nu}_e}$  in  $\bar{\nu}_e$  and total emitted energy,  $\epsilon_T$  (assuming  $N_\nu = 3$ ) versus temperature for Kamioka and IMB data, allowing for statistical errors as well as systematic shifts due to possible electron scattering events and variations in threshold and efficiency assumptions. Note overlap region is a good fit to the standard model.

Table 1: Neutrino Data		
Time (UT) February	Detector (threshold*/size)	# of Events ( <i>E</i> -range/Duration)
23 2h 52m "±1 min " "	Mt. Blanc (7 MeV/90 T) <sup>+</sup> Kamioka (8 MeV/2.14 kT)  IMB (30 MeV/6.8 kT) Baksan (11 MeV/130 T) <sup>+</sup>	5 (6-10 MeV/7 sec) 1 (7 MeV/10 sec) (consistent w/background) none reported none reported
23 7h 35m (± min) 23 7h 35m " "	Kamioka (7 MeV/90 T) IMB (30 MeV/6.8 kT) Baksan (11 MeV/130 T) <sup>+</sup> Mt. Blanc (7 MeV/90 T) <sup>+</sup>	11 (7-35 MeV/13 sec) S (20-40 MeV/4 sec) 3 (12-17 MeV/10 sec) <sup>***</sup> 2 (7-9 MeV/13 sec)
sum of pulses	Homestake $\nu_e$ (0.7 MeV/615 T) <sup>**</sup>	0
	Optical	
23 9h 25m 23 10h 40m 24 10h 53m	lack of sighting photograph discovery	$m_\nu \gtrsim 8$ magnitude $m_\nu = 6$ magnitude $m_\nu = 4.8$ magnitude

\*Threshold is when efficiency drops to  $\lesssim 50\%$  (sub-threshold events are therefore possible).

<sup>+</sup>These detectors are liquid scintalators with  $H_{2n+n}C_n$ , thus have  $\sim 1.39$  more free protons than  $H_2O$  detectors of same mass.

<sup>\*\*</sup>The Homestake detector is only sensitive to  $\nu_e$ 's. It is made of  $C_2Cl_4$ .

<sup>\*\*\*</sup>Three fiducial volume events, 5 total volume events.

# The Mt. Blanc Burst

